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A STRUCTURAL-MEMBER LEVEL ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF TIMBER, REINFORCED CONCRETE AND STEEL IN BUILDING CONSTRUCTION

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ABSTRACT: This study evaluates and compares the environmental impact of timber, concrete, and steel as building materials. This study designed a target member (beam) with equivalent structural performance under the same design conditions, such as span and live load, and compared the environmental impact. The carbon footprint analysis was conducted using Life Cycle Assessment (LCA) methodology, with a functional unit of 1-meter length of the designed beam and a cradle-to-gate system boundary. The study found that timber has a lower carbon footprint than steel and concrete, with the lowest carbon emissions during the product stage. Notably, the study also found a significant difference between the two environmental impact comparison methods, unit volume-based and structural performance-based. The findings demonstrate the sustainability of timber in high-rise construction and its potential to contribute to carbon neutrality while offering exceptional engineering capabilities. Further research is needed to improve the structural assumptions and LCA to evaluate the environmental impact of building materials more accurately.

KEYWORDS: Environmental Impact, Timber, Concrete, Steel, LCA, Equivalent structural performance

1 INTRODUCTION

The construction industry has recently been focusing on environmental concerns, such as climate change and global warming, leading to a growing emphasis on assessing the environmental impact of building materials. The building sector dramatically impacts the environment, accounting for over 40% of global energy consumption and roughly 30% of greenhouse gas emissions [1]. As a result, the building sector must take responsibility and play a role in addressing the challenge of climate change. Timber presents a range of substantial environmental advantages over other building materials, emitting fewer greenhouse gases during production and serving as a carbon sink. As a result, timber has gained recognition as an environmentally friendly material that has the potential to contribute to carbon neutrality while offering exceptional engineering capabilities. Despite its potential benefits, the utilization of timber in modern high-rise construction is still in its early stages, and there remains a need for a deeper understanding of its comparative environmental impact when compared to other building materials, such as steel and concrete.

Evaluating timber as a building material from an environmental perspective poses several challenges. One of the significant difficulties is that direct comparison of the environmental impact of buildings is limited. This is because the total environmental impact of a building is influenced by a multitude of factors, such as size, energy consumption during use, and the materials used. It is often difficult to determine the relative impact of each factor. In addition, the number of timber buildings is smaller than that of other buildings, limiting statistical analysis. Some researchers have attempted to address this challenge by utilizing a methodology that compares the environmental impact of existing buildings virtually by redesigning them as equivalent buildings of the same usage and layout [2-3]. However, this methodology may have limitations as there is no guarantee that the structural system of a building designed with a different material will be as efficient as the original building.

Consequently, this study aims to compare the environmental impact of timber as a building material with steel and concrete. Structural members were designed to achieve this with equivalent performance under controlled design conditions while considering the mentioned issues. Furthermore, this study aims to comprehensively understand the sustainability of timber in modern high-rise construction and identify each material's strengths and weaknesses.

2 STRUCTURAL DESIGN

2.1 TARGET MEMBER AND EQUIVALENT STRUCTURAL PERFORMANCE

This study designed members with equivalent structural performances and compared their environmental effects.

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To objectively compare the environmental impact of different materials, selecting a target for comparison and defining equivalent structural performance as a criterion is necessary.

As a specific building was not designated in this study, making necessary assumptions may become complicated and increase research limitations. Hence, due to its relatively simple design conditions, the target member was selected as a beam supporting mainly gravity loads.

Even though beams with different materials may have different moment and shear strengths, they can provide the same space and function as long as their design conditions, such as span and load, are the same. Thus, in this study, equivalent structural performance was defined through design conditions, not calculated indicators such as moment and shear strength. Additionally, all members were designed to have similar depth as steel beams using Products produced according to standard specifications, even if the structural performance is the same. This was done to ensure that the overhead clearance is not greatly affected, as a difference in beam depth would result in a difference in usable space, as shown in Figure 1.

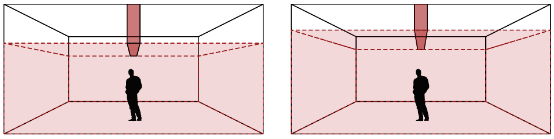

(a) (b)

Figure 1: *Example of usable space and overhead clearance according to beam depth: (a) large beam depth, (b) small beam depth.*

2.2 MATERIALS

Three types of materials were used in the beam design: timber, steel, and reinforced concrete (RC). The timber beam was assumed to a glued-laminated timber (GLT) using larch (*Larix kaempferi*), a mechanically graded dimensional lumber. The materials used in the design are listed in the following Table 1, and the design was based on the KS standard [4–7]. All materials were chosen from those commonly used in the industry. The dead load was calculated using the density data from the Ministry of Land, Infrastructure, and Transport [8].

Table 1: *Material properties*

Type	Material	Density [kg/m^3]	Strength [MPa]	MOE [MPa]
Timber	10S-30B	580	10 (f_b)	9,000
Steel	SM355A	7,850	355 (f_y)	210,000
RC	C30	2,300	30 (f_{ck})	27,500
	SD400	7,850	400 (f_y)	200,000

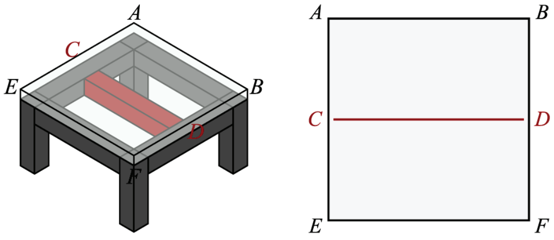
Where MOE=modulus of elasticity, f_b=bending strength, f_y=yield strength, f_{ck}=compressive strength.

2.3 STRUCTURAL MEMBER DESIGN

The beams were designed based on the following structure (Figure 2). In order to simplify, it was assumed that the plane has a square shape and that the beam is located at the center. The design was carried out considering a span ranging from 3 to 8 meters and a live load ranging from 2 to 6kN/m^2. The design followed the Korean design standard (KDS), and the timber structure was designed using the allowable strength design (ASD) method. In contrast, the steel and concrete were designed using the ultimate strength design method (USM) and the load and resistance factor design method (LRFD), respectively. In order to design optimally, All beams were designed with the minimum member weight in each condition.

The following assumptions were additionally made in the design:

1) The shape of the timber and concrete beams was rectangular, and the shape of the steel beams was an I-beam (Figure 3).
2) The beams were assumed to be a simple beam condition in which all boundary conditions are pin connections and were designed only for dead and live loads.
3) The slab's weight was calculated by designing a CLT slab for timber and a concrete slab for RC and steel. The weight of the finishing and equipment was not included.
4) Fire-resistance design was not considered.



(a) (b)

Figure 2: *Assumed structural diagram for the beam design: (a)elevation and (b)floor plan.*

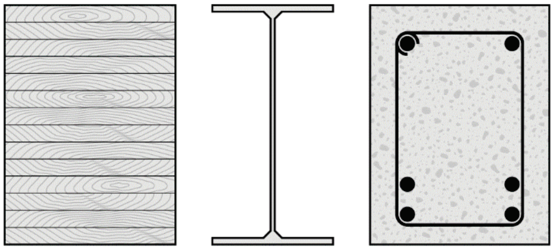

(a) (b) (c)

Figure 3: *Cross-sectional schematic diagram of beams designed for (a)GLT, (b)Steel, and (c)RC.*

3 CARBON FOOTPRINT ANALYSIS

3.1 FUNCTIONAL UNIT AND SYSTEM BOUNDARY

This study evaluated the environmental impacts by carbon emissions through Life Cycle Assessment (LCA) methodology. To perform LCA, defining a functional unit and a system boundary is necessary. The functional unit was set as the 1-meter length of the designed beam, and the final quantity was calculated by dividing the total quantity of the beam by the span. The system boundary was defined as cradle-to-gate (product stage), and only the environmental impacts during raw material extraction and processing, transportation, and manufacturing were considered (Figure 4). The reference service life of the building was assumed to be 50 years.

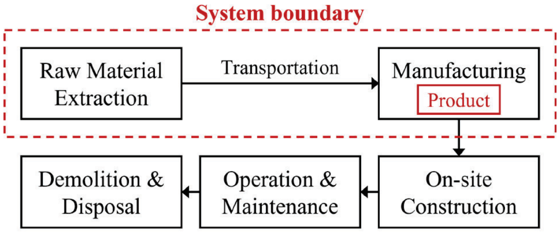


Figure 4: Building life cycle and system boundary.

3.2 CARBON EMISSION EVALUATION

The data used to evaluate the carbon emission was taken from a publicly accessible environmental product declaration (EPD) database. The carbon emission data of steel and concrete materials were obtained from the database of the Ministry of Environment. In contrast, data for GLT was taken from the database of the Forest Science Institute, as there was no EPD database available in Korea. The used data is presented in the following Table 2. The total CO_2 emissions were calculated by multiplying the material quantities by the CO_2 emissions factor per unit.

Table 2: The equivalent carbon emission factor of materials

Material	CO_2 emission	Unit	Reference
GLT	87.64	$kgCO_2$-eq/m^3	[9]
Steel	11,241		[10]
Concrete	3,532		[10]
Rebar	259		[10]

3.3 LIMITATIONS

This study has similar assumptions as previous studies [11], and similarly, it has the following limitations:

1) This study used the equivalent carbon emission factor from the EPD database developed in Korea. This study did not account for environmentally improved products such as low-carbon concrete. Therefore, it is essential to note that the results may be limited to the conditions of Korea at the time of this study. Production processes, transportation methods, and efficiencies vary by region and time, which may result in different findings from this study.
2) The system boundary of this study was limited to the product stage, from raw material extraction to manufacturing, thereby excluding the impact in the use and disposal stages.
3) The findings of this study should be separate from other building components (e.g., columns) or structural systems (e.g., continuous structural systems). For instance, vertical members, such as columns and walls, are highly influenced by upper-level loads. Thus, an increase in load caused by the building size, material density, and member volume increases, leading to an increase in the cross-sectional size of the vertical member. Additionally, the moment distribution in the member may change for a continuous structural system, which could result in different findings. This study also did not apply any load factor to timber beam design.
4) It is also important to note that this study did not consider the fire-resistance design. Therefore, the findings may not be suitable for fire-resistance design purposes.

4 RESULTS AND DISCUSSIONS

4.1 COMPARISON CARBON EMISSIONS ACROSS SPANS

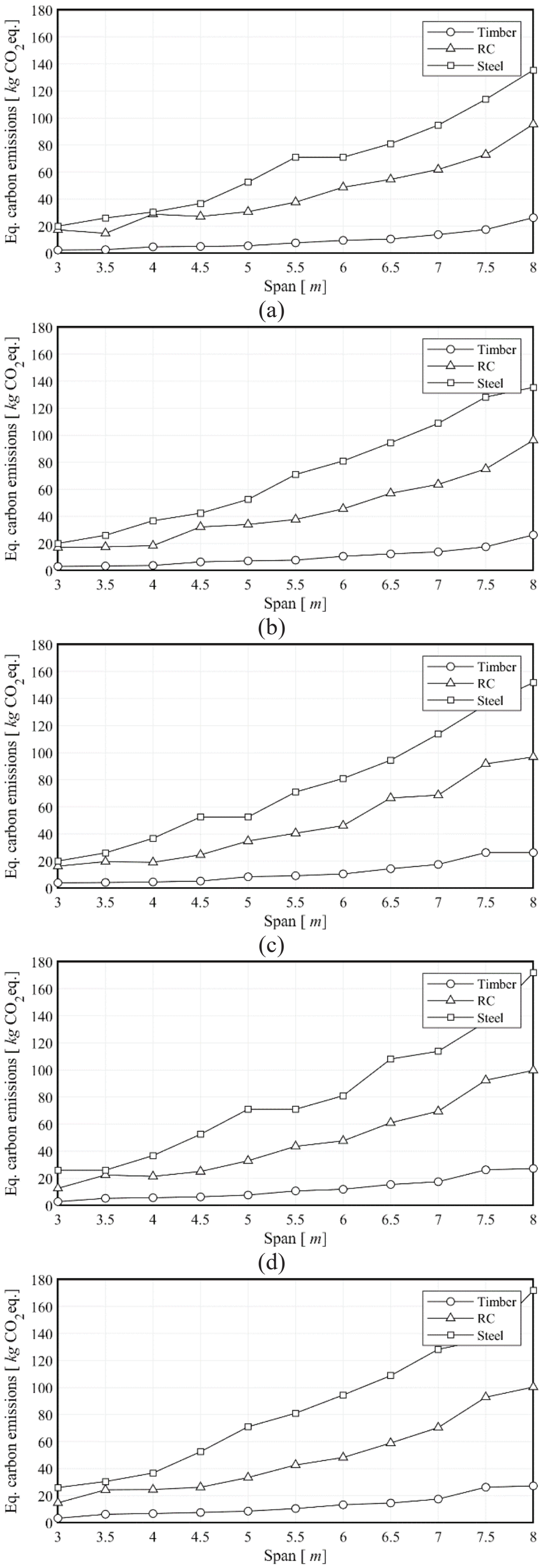
Figure 5 presents the carbon emissions results along the span for each live load. As the span increased, a greater structural performance was necessary, which led to an increase in the cross-sectional size and quantity of materials, and consequently resulted in a rise in carbon emissions. The analysis indicates that GLT emitted the lowest carbon across all scenarios with equivalent structural performance, while RC and Steel followed in that order.

To clearly compare the ratio between each material, the data was normalized by the steel, which has the highest carbon emission, as shown in Figure 6. The results indicate that, on average, timber and RC exhibited a reduction of 85.52% and 37.29% in carbon emissions compared to steel.

Although no distinct patterns in carbon emissions were discernible across the span, the data indicated the presence of fluctuations. The observed fluctuations in the results can be attributed to discontinuities in the cross-sectional design of the beams. Since steel beams were used as ready-made products, the section properties were not continuous across spans. Furthermore, considering the workability, the cross sections of timber and RC were designed with 10mm increments. Consequently, the strength-to-load ratio of each beam differed across spans, leading to the observed fluctuations.

4.2 COMPARISON CARBON EMISSIONS ACROSS LIVE LOADS

In Figure 7, the equivalent carbon emissions along the live load are shown for a span length of 6m. It was observed that the change in carbon emissions along the live load is



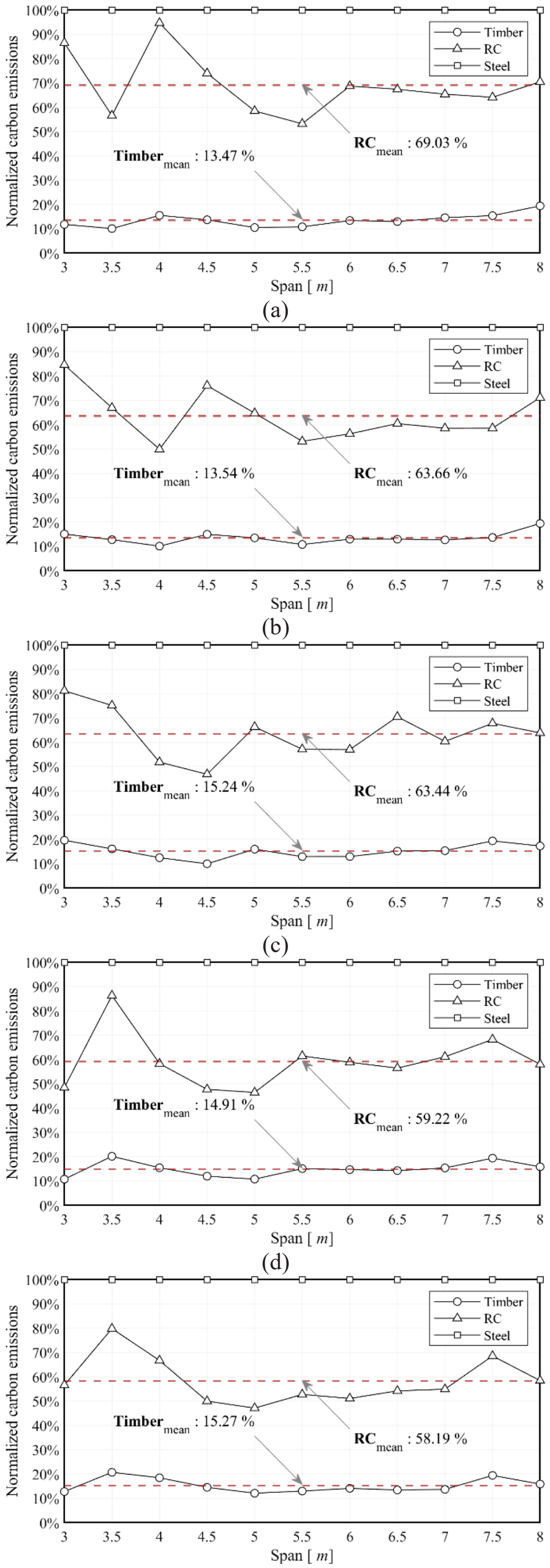
(a)

(b)

(c)

(d)

(e)



(a)

(b)

(c)

(d)

(e)

Figure 5: *Equivalent carbon emissions along the span when the live load was (a)2kN/m^2, (b)3kN/m^2, (c)4kN/m^2, (d)5kN/m^2, and (e)6kN/m^2.*

Figure 6: *Normalized equivalent carbon emissions along the span when the live load was (a)2kN/m^2, (b)3kN/m^2, (c)4kN/m^2, (d)5kN/m^2, and (e)6kN/m^2.*

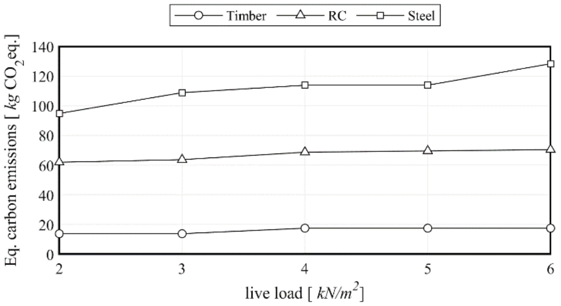


Figure 7: *Equivalent carbon emissions along the live load when the span was 6m.*

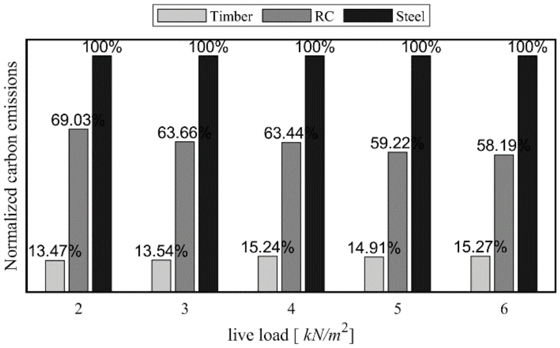
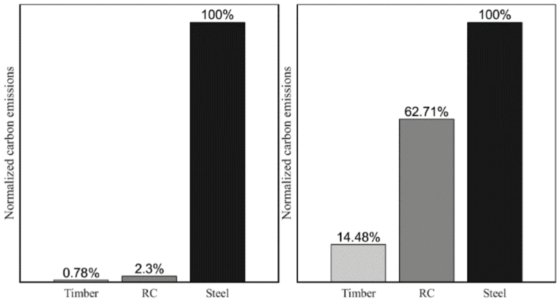


Figure 8: *Comparison of normalized equivalent carbon emissions along the live load.*



(a) (b)

Figure 9: *Comparison of normalized equivalent carbon emissions by (a)volume-based and (b)performance-based comparisons.*

not greater than the change along the span. This arises from the influence of live load and span on required strength and deformation. The required strength and deformation increase proportionally to the load's first power. In contrast, the required strength increases proportionally to the span's square, and the deformation increases proportionally to the span's fourth power. Consequently, the required structural performance was predominantly influenced by the span, resulting in a more pronounced alteration in the environmental impact as the span varied, compared to the effects caused by changes in the live load.

Figure 8 also presents the average normalized equivalent carbon emissions along the live load. In this case, the changes in carbon emissions caused by the live load were not substantial, and no distinct patterns could be identified as well.

4.3 CARBON EMISSION RATIOS FOR SUSTAINABLE BUILDING MATERIALS

Figure 9 reveals that the carbon emission ratio by material varies significantly between a unit volume-based comparison and a structural performance-based comparison. This difference can be attributed to the specific structural performance of each material, indicating that direct comparisons of carbon emissions per unit volume may lead to substantial errors.

Notably, when comparing the results of volume-based and performance-based comparisons, there has been a decrease in the steel/timber ratio and an increase in the RC/timber ratio. This observation may suggest that, from an environmental standpoint, the structural efficacy of timber is relatively inferior to that of steel but superior to that of RC. Such a finding may have significant implications for sustainable construction practices, as it highlights the potential of timber as a viable alternative to traditional building materials, particularly in the context of reducing the carbon footprint of construction projects.

5 CONCLUSIONS

In conclusion, this study analyzed and compared the environmental impact of timber, concrete, and steel in building construction at the structural member level. The results revealed that timber and concrete had significantly lower equivalent carbon emissions than steel, with timber having the lowest emissions. Although the carbon emissions of all materials increased with the increasing span, there was no specific trend according to span and live load.

A significant difference was observed when comparing the environmental impact ratio of volume-based and performance-based comparisons. This indicates that the structural efficiency of timber was found to be relatively inferior to steel but superior to concrete. This finding suggest that timber could be a feasible alternative to conventional building materials and could have important implications for sustainable construction practices.

However, this study has limitations, and further research is required to improve the structural assumption and life-cycle assessment. Future studies should consider diverse structural systems, design conditions, and target members. Furthermore, comprehensive life cycle assessments covering various impact categories should be conducted to obtain a more comprehensive understanding of the environmental impact of these building materials.

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